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# CHARACTERIZATION OF THE 20-Ah NICKEL-CADMIUM CELL USED FOR ENERGY STORAGE ON THE ORBITING ASTRONOMICAL OBSERVATORY

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Floyd E. Ford

Space Power Technology Branch  
Engineering Physics Division

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**ABSTRACT**

Tests were conducted on 20-Ah sealed nickel-cadmium cells to evaluate initial and long-term performance at various charge rates, temperatures and voltage-control levels. An average ampere-hour recharge of 103 percent per orbit at 13°C was able to maintain cell capacity; required watt-hour recharge on an orbital basis was 8 to 10 percent greater than required ampere-hour recharge. Cells exhibited an early life "burn-in" characteristic. A discharge after periods of repetitive cycling yielded two voltage plateaus which were temporarily eliminated by the discharge. There was a degradation in the amount of watt-hours a battery will store with life, but the amount of watt-hours attainable on discharge to 1.0 V/cell at any specific point in the life is essentially constant, the difference being the voltage at which the watt-hours can be attained.

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# CHARACTERIZATION OF THE 20-Ah NICKEL-CADMIUM CELL USED FOR ENERGY STORAGE ON THE ORBITING ASTRONOMICAL OBSERVATORY

## INTRODUCTION

In early 1967, an extensive investigation was initiated at the United States National Aeronautics and Space Administration Goddard Space Flight Center (NASA/GSFC) to determine the characteristics of the 20-Ah sealed nickel-cadmium cells used for energy storage in the Orbiting Astronomical Observatory (OAO) program. The need for a comprehensible characterization was fully recognized with the premature failure of batteries used on OAO 1. Although the battery failure was attributed to the charge-control system, secondary failures were found to result from a lack of understanding of the parameters associated with battery charging. The investigation and cell-test program that followed have provided some new insight into the performance of nickel-cadmium batteries for space applications. During the test program, several significant factors in the design and use of spacecraft batteries were observed.

## TEST DESCRIPTION

### Phase I: OAO 2 Flight Batteries (Battery Assemblies 25A and 26A)

In the initial phase of the test program, typical parameters related to the flight battery in orbital use were simulated. After completion of flight-acceptance testing on the flight lot of cells, five cells representative of the lot were selected for parametric testing. The test parameters were (Ford 1970a) a cycle time of 90 min (30 min discharge, 60 min charge), a depth of discharge of 15 percent (6.0 A for 0.5 hr), a charge rate of  $C/4^*$  (5 A) to  $C/2.5$  (8 A) and temperatures of 0°C, 15°C and 32°C. Over 70 percent of the total cycles completed during phase I (6091) were conducted at 15°C or lower.

### Phase II: OAO 3 Flight Batteries (Battery Assemblies 32 and 33, 34 and 35)

The second phase of the test program was a continuation of phase I, with new cells from two subsequent flight lots. As a result of the experience gained from phase I, phase II was made more detailed and comprehensive. The test conditions for this phase are listed in Table 1 (Ford 1970b). Three five-cell

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\*The factor C is the rated capacity of the cell; i.e., the ampere-hour capacity at the 2-hr rate.

Table 1  
Parametric Test Matrix for OAO 3 and 4 Cells\*

Test Temperature (°C)	Equivalent BVLS**	Volts per Cell	Pack Current (A)	
			Charge	Discharge
1.6	4	1.488	4	5
	1	1.451		
	8	1.538		
	4	1.488	8	5
	1	1.451		
	8	1.538		
	4	1.488	12	5
	1	1.451		
	8	1.538		
12.8	4	1.446	4	5
	1	1.410		
	8	1.494		
	4	1.446	8	5
	1	1.410		
	8	1.494		
	4	1.446	12	5
	1	1.410		
	8	1.494		
21.1	4	1.415	4	5
	1	1.381		
	8	1.463		
	4	1.415	8	5
	1	1.381		
	8	1.463		
	4	1.415	12	5
	1	1.381		
	8	1.463		

\*Fifteen-percent depth of discharge for all tests; 65-min light period, 35-min dark period each orbit.

\*\*Battery-voltage limit systems (provide the eight discrete temperature-compensated voltage levels referred to in text).

packs were included in the test program, two to assess the effects of temperature sequence (high to low vs low to high) and the third to compare third-electrode charge control with voltage control.

Upon completion of the tests, the packs were again subjected to a capacity cycle at the three temperatures and an overcharge test at 1.6°C. With the cell-verification test completed, cycling was continued at 13°C under "nominal" conditions to study long-term effects of repetitive cycling. The selection of the 13°C temperature was based on the predicted operating battery temperature in flight of 10°C to 15°C.

All test packs contained five cells, two of which contained third electrodes. Three of the five cells were instrumented with pressure transducers for continuous recording of pressure. The remaining two cells were equipped with compound gages from which pressure was recorded at the end of each test condition.

Charging of each pack was accomplished by a "modified taper charge" method. This consists of charging with a current limit until a preset voltage limit is obtained, at which time the current "tapers" to some value that is dependent on the voltage chosen for control. Throughout the test program, voltage, current and temperature were the dependent variables, with ampere-hours returned (percent recharge) each cycle being the independent variable. The depth of discharge was held constant at 15 percent of the 20-Ah rated capacity.

## TEST RESULTS

The test results of phases I and II can be combined and discussed in two categories: (1) charge characteristics and (2) discharge characteristics. The interpretation of the volume of data resulting from this program would not be possible without this generalization.

### Charge Characteristics

With a voltage-limit/current-limit (modified taper) charge control as found on OAO 2 through 4, the ampere-hour percent recharge possible on an orbit-by-orbit basis is dependent on such parameters as voltage limit, charge current, temperature and depth of discharge. Figure 1 illustrates the percent recharge  $[(Ah \text{ in}/Ah \text{ out}) \times 100]$  obtained when cycling cells with various voltage limits for charge control (Ford 1970b). The voltages shown are indicative of the eight discrete temperature-compensated voltage limits (Ford 1972) available for charging the three batteries in the OAO (2 through 4) system. The two charge rates were selected to bracket the "nominal" range of charge currents available



to recharge each battery. Values shown (lower left-hand corner) as minimum recharge to maintain battery capacity at 0°C, 15°C and 32°C were based on known technology at the time (1969) these particular tests were conducted. It has been demonstrated during life test that the percent recharges shown were sufficient to maintain battery capacity (Christy and Harkness 1971). Values for recharge exceeding those shown did not improve the capacities obtained during the cycle-life program. As will be demonstrated, the minimum values shown are somewhat higher than the minimum values known today.

One point of particular interest but not obvious from Figure 1 is the increase in sensitivity of percent recharge to voltage with increasing temperature. These data suggest that charging batteries with a voltage control requires a more precise control voltage at higher temperatures than at lower temperatures in order to maintain the same relative degree of control. When percent recharge is equated to overcharge, the significance of a  $\pm 0.010$  V/cell tolerance on a voltage-limit charger can be interpreted as a 16-percent variation in overcharge at 32°C as compared with a 4-percent variation at 0°C. These data explain some of the design problems associated with voltage charge control at moderate to high temperatures, to say nothing about the effect of high temperature on battery life.

Figure 2 illustrates the percent recharge obtained for the cell lot manufactured for OAO 3 batteries when tested under the conditions in Table 1. These data differ from those of Figure 1 in that the test program was revised to reflect changes in battery-charging parameters from OAO 2 to OAO 3 (Ford 1971). In particular, the upper test temperature was decreased from 32°C to 21°C and the 15°C temperature was decreased to 13°C. The charge-rate range was increased to include three charge rates, namely 4, 8 and 12 A. Both changes were made to bring the ground-testing conditions closer to predicted flight parameters. One further change that should be noted is that the range of voltage available for charging on OAO 3 (Fig. 2) is greater than that shown for OAO 2 (Fig. 1) because of a decrease in the spacecraft lower voltage-control level. This reflects a change made in the OAO 3 battery-charger design as a result of flight experience with the OAO 2 batteries. The eight discrete voltage-limit levels were modified by increasing the voltage spread between each level such that the lowest control level was shifted down in voltage by a value equivalent to the original separation between each level. As a result of this change, the charge-control voltage for OAO 3 and subsequent spacecraft can now charge the batteries in flight at recharges indicated by those shown as minimum values (Fig. 2).

The recharges shown as minimum to maintain battery capacity are indicative of the current generation of nickel-cadmium cells.\* It is emphasized that this does not mean that nickel-cadmium cells manufactured today are more efficient (ampere-hour) than cells of the past. What the data do suggest is that our understanding of the characteristics of nickel-cadmium cells manufactured for aerospace applications has improved. Cells cycled with the suggested recharge percentage have shown excellent capacity retention for many thousands of cycles.

An additional factor can be examined from the data in Figure 2: the effects of a wide range of charge currents on the percent recharge with voltage charge control. As the charge rate approaches  $C/2$ , no additional gain in recharge capability is realized for the condition these data represent. As the recharge percentage approaches the minimum required, the amount of recharge obtained for the orbital cycling shown becomes less sensitive to charge rate and voltage-control level.

Ratings in ampere-hours are very commonly used by battery designers and manufacturers to describe batteries. However, satellite power-system designers deal in watts and watt-hours in sizing batteries for spacecraft loads and in making calculations for system energy balance. During the course of the parametric study, it became obvious that a relationship between ampere-hours and watt-hours existed that would be useful to both the system and battery design. Figure 3 illustrates the watt-hour percent recharge obtained for the various ampere-hour percent recharges shown previously (in Fig. 2). The data points represent the relationship for the test conditions in Table 1. Two significant facts are evident: (1) The relationship between watt-hour recharge and ampere-hour recharge is linear and independent of temperature, charge rate and voltage (for the range of values shown), and (2) the watt-hour recharge on a cyclic basis is always 8 to 10 percent greater than the ampere-hour recharge. Thus, the watt-hour performance of nickel-cadmium batteries is directly related to the ampere-hour performance; e.g. for a battery to yield long cycle life with 103-percent ampere-hour recharge, the watt-hour recharge required will be 113 percent. The relationship shown is for 15-percent depth of discharge. The exact relationship to depth of discharge was not determined; however, it is believed that although the minimum ampere-hour recharge required is somewhat dependent on depth of discharge, the relationship shown in Figure 3 is not. Further insight is provided by examining charge-efficiency data for 100-percent depth-of-discharge cycles which show the best efficiency obtainable is 92 to 93 percent (Bruess 1968). This suggests that the ampere-hour efficiency is in fact

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\*J. Harkness, U.S. Navy Ammunition Depot, Crane, Indiana, private communication.

related to depth of discharge. Test data from the OAO program on similar type cells have demonstrated a cyclic efficiency at 15-percent depth of discharge greater than 96 percent at 13°C. Recently, OAO cells on life test yielded approximately 30.0 Ah of capacity after cycling 1 year at 20°C; the average recharge was 106 percent during the test period.\* The efficiencies demonstrated in this program for the 20-Ah cells exceed any other values reported to date.

Early in the OAO test program, it was observed that the ampere-hour percent recharge for a specific test condition showed a gradual increase during the first few hundred cycles. This phenomenon was observed during the first series of verification tests. Figure 4 shows the ampere-hour percent recharge for 400 days (5600 cycles) of test on production lot 32, 33 and 196 days of test on production lot 34, 35. The tests on the two different lots were conducted over a year apart. Unfortunately, during the test on cell lot 32, 33, the specific set of conditions shown in Figure 4 was not tested often enough to provide sufficient continuity in data to show the complete trend. After it was learned that the ampere-hour recharge varied with life, subsequent verification tests were conducted, with more emphasis on characterizing the change. Data for lot 34, 35 clearly show what is apparently a "burn-in" period before cycling stability results. For this lot, it required approximately 100 days for the percent recharge to reach a stable condition. It is significant to note that a very large percent of the observed change in percent recharge for both lots occurred during the first 20 days (280 cycles) of test. As a result, one can conclude that it is both feasible and practical to allow for the initial changes (burn-in) to occur in a test program prior to conducting parametric test. It is now standard procedure on parametric test to allow approximately 4 weeks for burn-in cycling prior to establishing data to represent cell characteristics. It has been observed that a complete discharge will partially negate the effect of burn-in cycles; i.e., if the cycling is interrupted by a capacity discharge (to 1.0 V/cell), a similar trend will be observed in the percent recharge upon returning to cycling, but the magnitude of change will be less than that originally observed for new cells. For this reason, the number of capacity discharges was minimized during the latter part of this program.

### Discharge Characteristics

At the onset of this program, little was known about the exact degradation in discharge voltage and ampere-hour capacity of the cells after extended periods of repetitive cycling. The degradation was of particular importance to the OAO program since the mission required that the batteries be operated at a

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\*J. Harkness, U.S. Navy Ammunition Depot, Crane, Indiana, private communication.

state of charge as low as 50 percent, resulting from successive orbits of low charge current.

During phase I testing (OAO 2), the five-cell pack was discharged at various intervals during the cycling test to observe the effects of continuous cycling on the discharge voltage and ampere-hour capacity. Figure 5 is a comparison of the initial new-cell ampere-hour capacity with that obtained after 627 continuous cycles (1437 total cycles). Note that the curves have two cycle-identification numbers: The larger number is the total number of accumulative charge-discharge cycles; the smaller number is the number of charge-discharge cycles completed since the last capacity discharge. The characteristics observed on discharge after 627 continuous cycles where the voltage decreases from approximately 1.16 V/cell to just above 1.0 V/cell were observed throughout the OAO cell-test program.

Figure 6 further illustrates the discharge voltage of cells after various numbers of consecutive cycles for a 6.0-A discharge. Curve 1 is used as a reference for discussion since it illustrates the discharge voltage after the greatest number of continuous cycles (1636) at 15-percent depth of discharge. The double- or two-plateau voltage can be positively identified from these data. Note that the voltage at the end of the 35-min discharge (15-percent depth of discharge) is 1.22 V/cell. The first, or upper, plateau occurs at approximately 1.18 to 1.19 V/cell, with the second, or lower, plateau occurring at approximately 1.05 V/cell. The maximum and minimum cell voltage during the transition between voltage plateaus is shown to illustrate that all cells do not respond identically. The first cell to decrease in voltage to the lower plateau is the highest ampere-hour capacity cell to 1.0 V. This characteristic prevails throughout the test program.

Following the discharge shown by curve 1, the cells were returned to cycling for recharge. After 28 cycles, a discharge was conducted to assess any change in the discharge-voltage characteristics. It is readily apparent from Figure 6 that the discharge voltage (curve 2) is significantly improved by the previous discharge. Even more significant is that although the discharge voltage is improved, the number of ampere-hours to 1.0 V is less than that obtained on the previous discharge when the cells exhibited the two plateaus and degraded discharge voltage. The ampere-hour limitation of a battery after extended cycling is primarily dependent on the definition of battery undervoltage. Another discharge was conducted after 110 cycles; the discharge voltage (curve 3) had decreased slightly below that for the previous discharge (curve 2).

Because the actual use of a battery in orbit does not provide for continuous constant-current discharge as performed in the preceding discharges, a "run-down" in battery capacity as would be experienced in orbit was simulated. This

was done by reducing the available charge current such that a net loss in capacity was realized each cycle. A total of 1003 continuous cycles was accumulated before the rundown was initiated. The charge rate was limited such that a net loss of approximately 2.2 Ah per orbit was realized. Curve 4 of Figure 6 illustrates the results. The similarity of the voltage profile of curve 1 for the constant-current discharge leads to the conclusion that the double plateau has reappeared, as indicated by the data for the cyclic rundown.

Following the rundown, the pack was allowed to recharge for 13 cycles by increasing the charge rate to 5.0 A. The pack was again discharged using a constant current (6.0 A). Data for this discharge are illustrated in Figure 7 for comparison with previous discharge data. The voltage profile for the discharge (cycle 4134) is very significant in that it reveals two distinct characteristics: (1) The discharge voltage, for up to 140 min of discharge time, is higher than that obtained during the equivalent period during cyclic rundown, and (2) the two-plateau effect was not eliminated by the partial cyclic rundown to 1.1 V/cell. What is apparent from the data presented is that the discharge voltage is only enhanced to the approximate depth of discharge reached by the pack on the cyclic rundown. When this depth of discharge is exceeded, the discharge voltage is at the same value that it would have been at had the cyclic discharge been continued to 1.0 V/cell. Note that the slight enhancement of discharge voltage during the first 140 min is obtained at an apparent ampere-hour loss to 1.0 V/cell when compared with the data for cycle 3074.

Data presented at this point were all obtained from ground testing, and even though every effort was made to be realistic in simulating flight conditions, the inevitable question is whether this happens in flight. Figure 8 shows a comparison of cell-test data with flight data from OAO 2. The accuracy of flight telemetry is such that the voltage vs ampere-hour data points could be in error by as much as one-half an ampere-hour. Nevertheless, the flight data for orbit 5625 follow the ground-test data very closely. Note that the lower plateau shown previously for the ground test does not appear in this figure. Extrapolation of the curve for orbit 5625 would indicate the flight battery voltage was approaching the transition from the upper to the lower plateau. By orbit 11 176, the battery voltage had degraded further, as indicated by the 7.7-Ah to 24.5 V (21 cells). It is noted that the lower plateau as observed during ground test would be evident in the OAO 2 data only under very adverse conditions. The equipment operating from the battery-voltage bus cannot function at voltages below approximately 1.15 V/cell, which is above the voltage of the lower plateau. Consequently considerable effort has been made to limit battery-capacity depletion to this region during the latter life of the spacecraft.

The previous data raise a question as to how the discharge voltage changes with cycle life; i.e., what happens with cells when no deep discharges are made

for periods up to a year or beyond? Figure 9 illustrates the discharge profile for four cells after completing a total of 5717 cycles. Cells 4 and 5 had been discharged to 1.0 V after 3152 cycles. Cells 2 and 3 had not received a discharge beyond the 3.0-Ah cycling depth during the 5717 cycles. The four cells were cycled in series and under the same test conditions. Cell 3 and to a lesser extent cell 2, which had experienced the greatest number of consecutive cycles, are lower in discharge voltage than cells 4 and 5. Although the ampere-hour difference in the "inflection point" (1.15 V) from the upper to the lower plateau between the two groups of cells is not what was expected, it does suggest that the rate of degradation is not linearly related to the total number of cycles and is different from cell to cell. Another point of interest, pointed out previously, is that the cells that reach the lower plateau first also have the greatest ampere-hour capacity to 1.0 V/cell.

What one can surmise from the information presented is that the degradation of discharge voltage with cycle life is probably asymptotic; i.e., the rate at which the inflection point (1.15 V/cell) between the upper and lower plateau is progressing toward the cycle depth of discharge is decreasing with increasing cycles. It has been observed that the entire discharge voltage with cycling is very dynamic with time, since not only is the inflection point shifting toward the cycling depth, but the overall discharge-voltage profile is gradually decreasing in magnitude.

The data discussed above have dealt with degradation in the discharge voltage and the onset of a double plateau with cycling. In nearly all cases where the discharge voltage had degraded, the ampere-hour capacity to 1.0 V/cell (or less) was slightly greater than that obtained with the same cells either before cycling or following a 100-percent depth-of-discharge cycle where the double plateau was erased. When the nickel-cadmium cell is considered as an energy storage device and not as an ampere-hour device, some very interesting observations can be made.

Illustrated in Figure 10 are the average watt-hour-per-cell relationship and discharge voltage for five cells. Data shown are for a precycling capacity discharge and after 2345 consecutive cycles. It is significant that although a degradation in discharge voltage had occurred during the 2345 cycles, the total number of watt-hours stored by the five cells was approximately the same as that on the precycling discharge. Another way of considering this is that the voltage degradation is not a degradation in total number of watt-hours stored, but in the watts per unit time the cell will deliver. Data illustrated in Figure 10 are for a relatively short life span compared with present NASA mission requirements. The long-term degradation of cells subjected to a repetitive cycling is even more interesting.

Data on watt-hour degradation with life are presented in Figure 11. The discharge voltages shown are for a 6.0-Ah rated capacity cell. The number of watt-hours storable prior to cycling is illustrated by the upper curve (1-10-69). The five cells were placed on life test under the conditions indicated. After 2 years (11 697 cycles) at 15-percent depth of discharge, the discharge portion of the cycle was extended to allow for a full discharge of the cells. A comparison of the discharge profile after 11 697 cycles with that obtained for the precycling reveals discharge degradation in two ways: (1) The average discharge voltage after 2 years has decreased by approximately 0.2 V/cell, and (2) the total number of watt-hours stored to 1.0 V is only 70 percent of that obtained for the precycling discharge. Subsequent to the discharge after 11 697 cycles, the five cells were recharged and discharged to assess the effects of the previous discharge. As shown, the previous discharge did enhance the subsequent discharge voltage; however, it did not return the voltage level to that obtained for the precycling test. Also, it is significant that the number of watt-hours available to 1.0 V was essentially the same on the first and second postcycling discharges. Although there is an apparent permanent and irreversible degradation in the watt-hour storage capability of nickel-cadmium cells with life, the number of watt-hours that can be stored at any given time (in this case, 2 years) in the life of the cell or battery is essentially the same. The difference is in the voltage level at which the battery will deliver the energy.

The data presented raise a very pertinent question as to the value of "reconditioning" batteries in space applications. From an energy consideration, there is apparently no gain from reconditioning. From a watts-per-unit-time standpoint, a full discharge will enhance the level of voltage at which the stored energy can be obtained. There is evidence that the enhancement of the discharge voltage is only temporary.\* There are also indications that for near-Earth orbit cycling as reported here, the more cycle life a cell or battery has experienced, the more temporary the improvement in discharge voltage will be. One additional comment regarding reconditioning: Cell-voltage divergence, although evident on the first postcycling discharge following 11 697 cycles, was much more severe during the second discharge. The data suggest that the risk of cell-voltage reversal is increased at deep depth of discharge immediately following a discharge-voltage conditioning cycle. Evidence is also available to support the theory that cells that have been subjected to long-term cycling (3 to 5 years) have a higher failure incidence during and immediately after a capacity discharge than during intervals where no capacity discharges occur.

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\*J. Dunlop, Communications Satellite Corporation, Gaithersburg, Maryland, private communication.

The approach at NASA/GSFC today is not to recondition in space, but rather to design equipment operating from the battery bus to be capable of functioning to an average of 1.0 V/cell at the battery terminals. With a very slight increase in the complexity of battery undervoltage protection, spacecraft will be capable of using practically all available stored energy in the batteries upon demand.

## CONCLUSIONS AND RECOMMENDATIONS

The feasibility of operating aerospace nickel-cadmium cells at very low ampere-hour percent recharge has been demonstrated. Although the exact minimum recharge for the OAO type 20-Ah cell was not determined, it was demonstrated that cells exhibited excellent capacity retention after periods of cycling exceeding 1 year when cycled at 104- and 106-percent recharge at 13°C and 20°C, respectively. The test conducted did not show conclusively that the minimum percent recharge required (or cyclic efficiency) was a function of depth of discharge; however, evidence was found to support this theory. It was shown that with voltage-limit charging, the sensitivity of ampere-hour recharge to the control voltage for the specific temperature increased by a factor of 4 when the temperature was increased from 0°C to 30°C.

The ampere-hour percent recharge for a specific set of test conditions changes with cycling, which suggests that nickel-cadmium cells require a burn-in test period. The change in percent recharge was observed to increase by 20 percent during approximately 80 days of test, with approximately 70 percent of the increase occurring during the initial 14 days of cycling. Parametric data obtained during the burn-in period are not representative of cell life performance and consequently should not be used in the design of battery chargers.

Watt-hour recharge was found to be linearly related to ampere-hour recharge on a cyclic basis and to exceed it by 8 to 10 percent for the various test conditions. From the minimum ampere-hour recharge data obtained during the test, the cell watt-hour cyclic efficiency was found to be about 85 percent for batteries operating at 13°C to 20°C.

A degradation in battery discharge voltage as characterized by the discharge voltage exhibiting two plateaus after various periods of cycling was identified. The exact voltage level of each plateau and the transition point between the upper and lower plateau are dependent on several variables, one being the number of accumulative cycles the cells have experienced at a specific depth of discharge. It was theorized with supporting data that although the magnitude of the discharge voltage of both plateaus shows some decrease with increasing cycle life, the transition region between the upper and lower plateau approaches the



cycling depth of discharge asymptotically. Increasing the depth of discharge (by extending the discharge time) was found to enhance the subsequent cycle discharge voltage but only to that depth to which the cells had previously been discharged.

Although a complete capacity discharge (to 1.0 V/cell) was shown to improve the discharge voltage, the improvement in voltage occurs at a slight reduction in ampere-hour capacity. After a few hundred cycles, the total number of watt-hours stored to 1.0 V was shown to be the same as that obtained on the precycling capacity discharge. The main difference observed was that the precycling watt-hours are obtainable at a normal voltage level but at less ampere-hour capacity than that obtained for cells exhibiting degraded or two-plateau voltage characteristics. Watt-hour degradation with life appears to be permanent and irreversible, but the total number of watt-hours stored at any given time in the life of a nickel-cadmium cell is essentially the same whether it is obtained at the lower, or degraded, voltage or at the improved, or reconditioned, voltage. Cells exhibit greater voltage divergence after the conditioning discharge, and there is an increasing frequency of failures associated with frequent capacity discharges after cells have been subjected to several years of life test. Therefore, reconditioning of batteries in flight is not recommended for current and/or future NASA missions.

Through a better understanding of both initial and long-term parameters of nickel-cadmium cells, 5-year missions of the near-Earth type at utilizations far exceeding designs of the past are now being flown or planned. Our desire is to continue to improve the basic technology associated with nickel-cadmium batteries through research and development, but it is equally important to make better use of our understanding of the technology available today. This has been the goal of the program presented.

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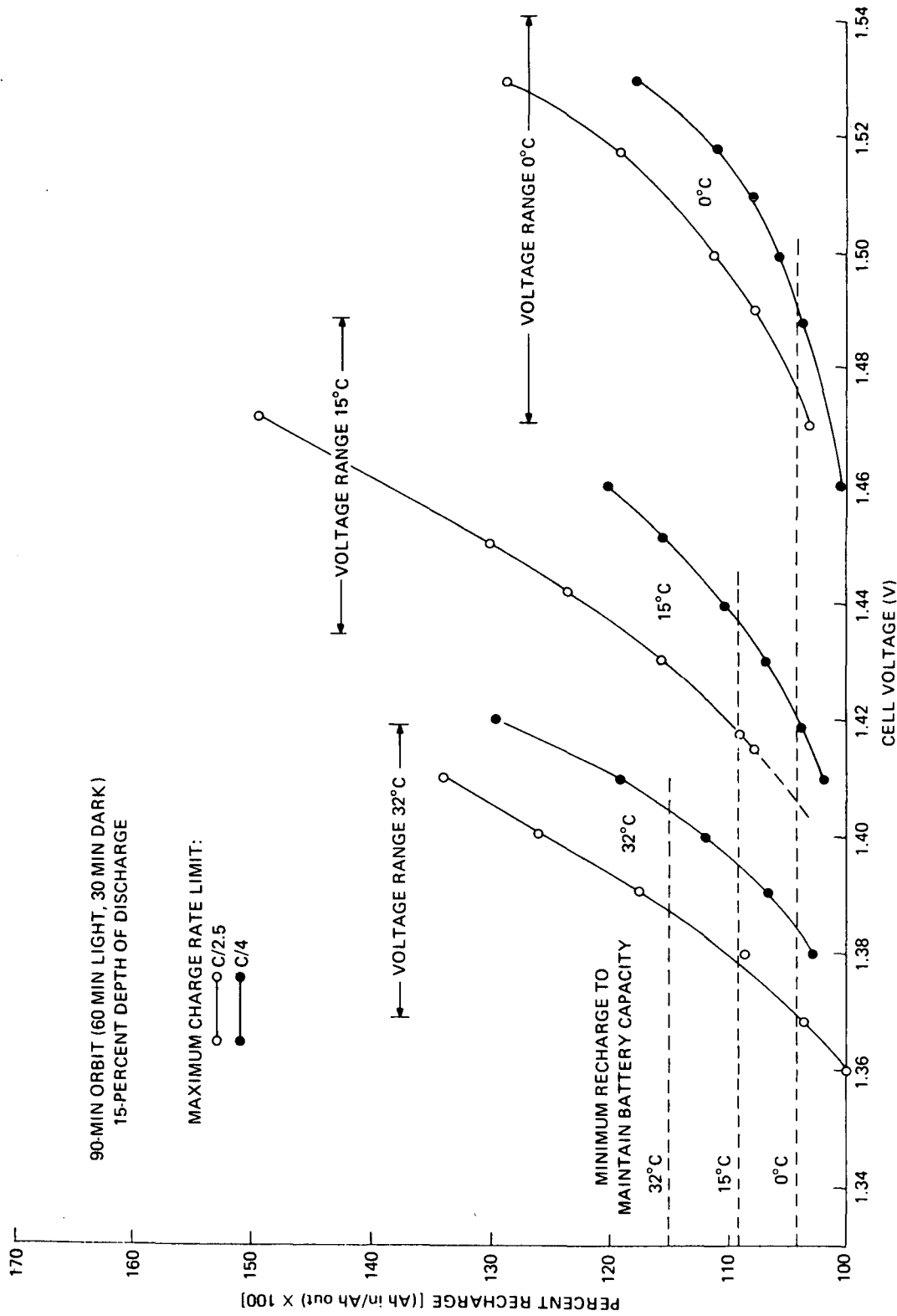


Figure 1. Ampere-hour percent recharge for voltage-limit charging of OAO 2 flight cells.

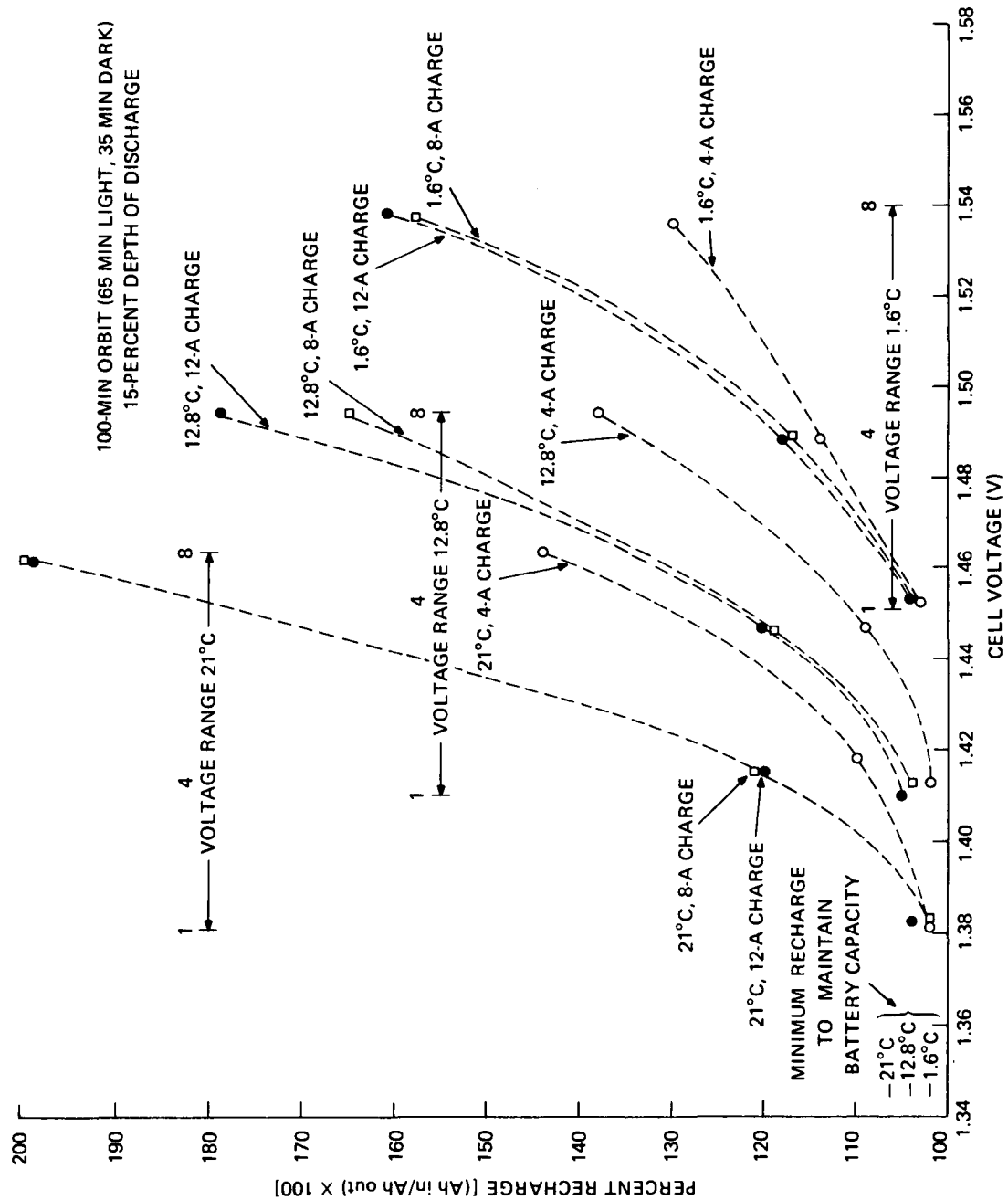


Figure 2. Ampere-hour percent recharge for voltage-limit charging of OAO 3 flight cells (battery assemblies 32 and 33).

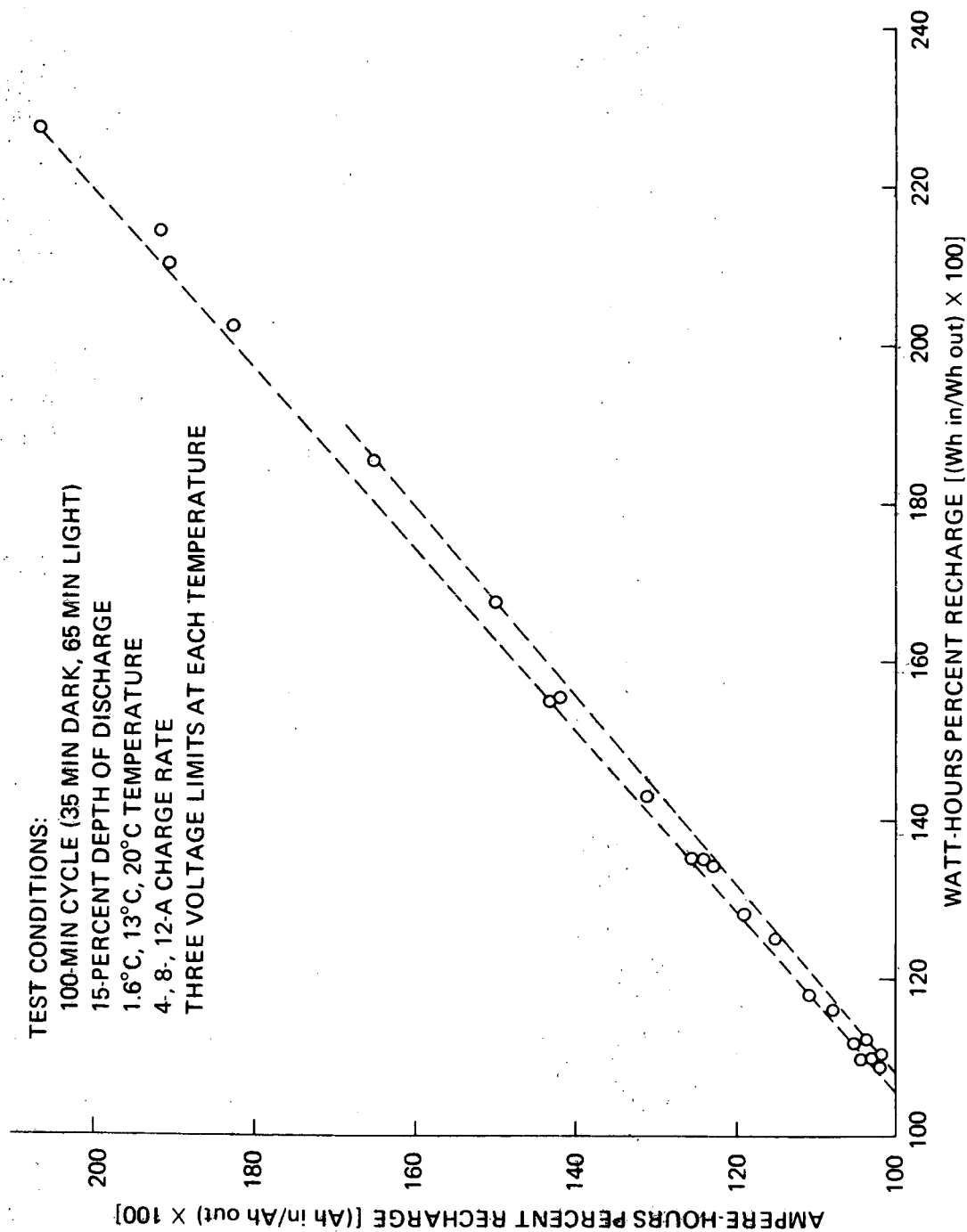


Figure 3. Ampere-hour vs watt-hour recharge for voltage-limit charging of OAO 3 cells (battery assemblies 32 and 33).

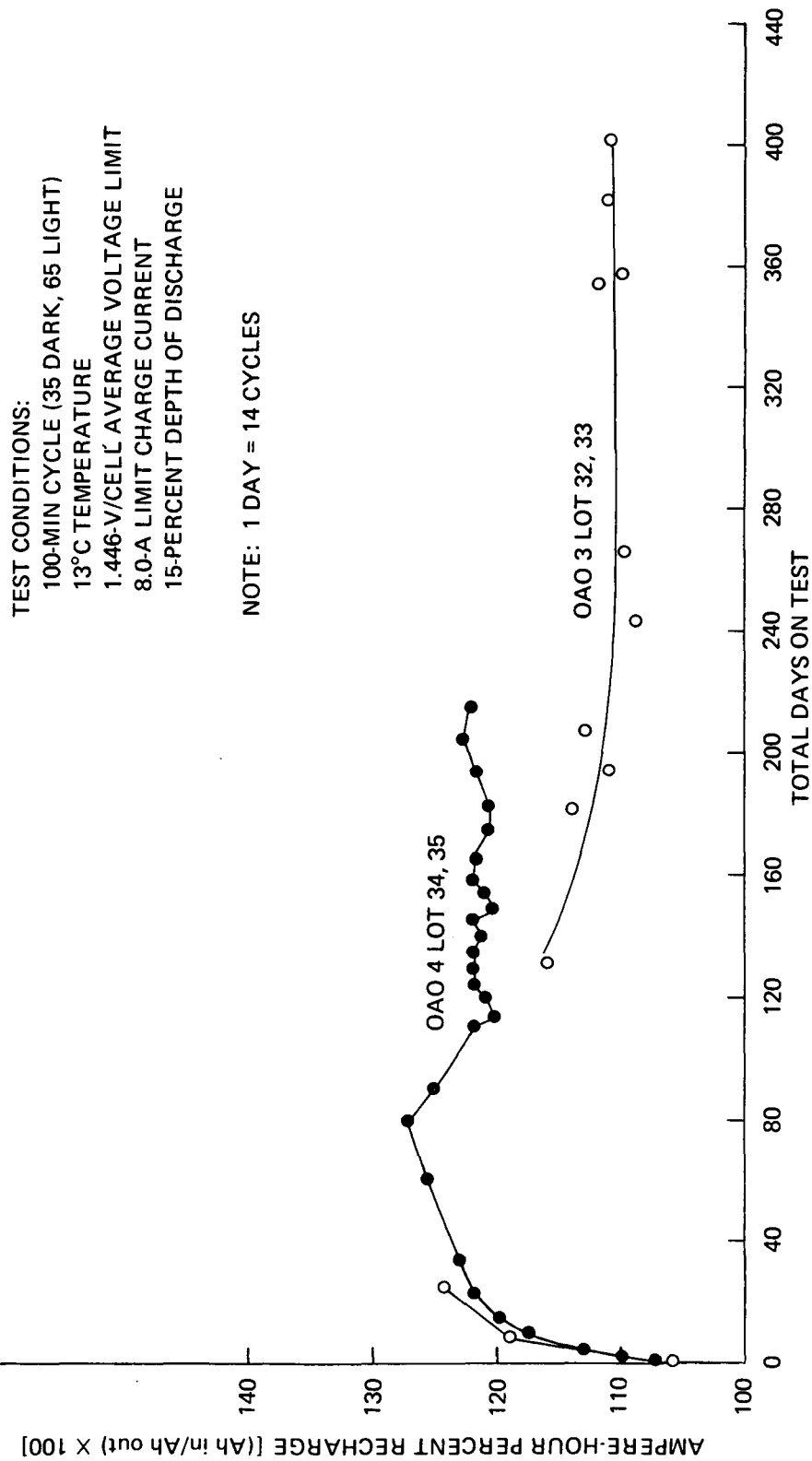


Figure 4. Changes in ampere-hour recharge characteristics with cycling.

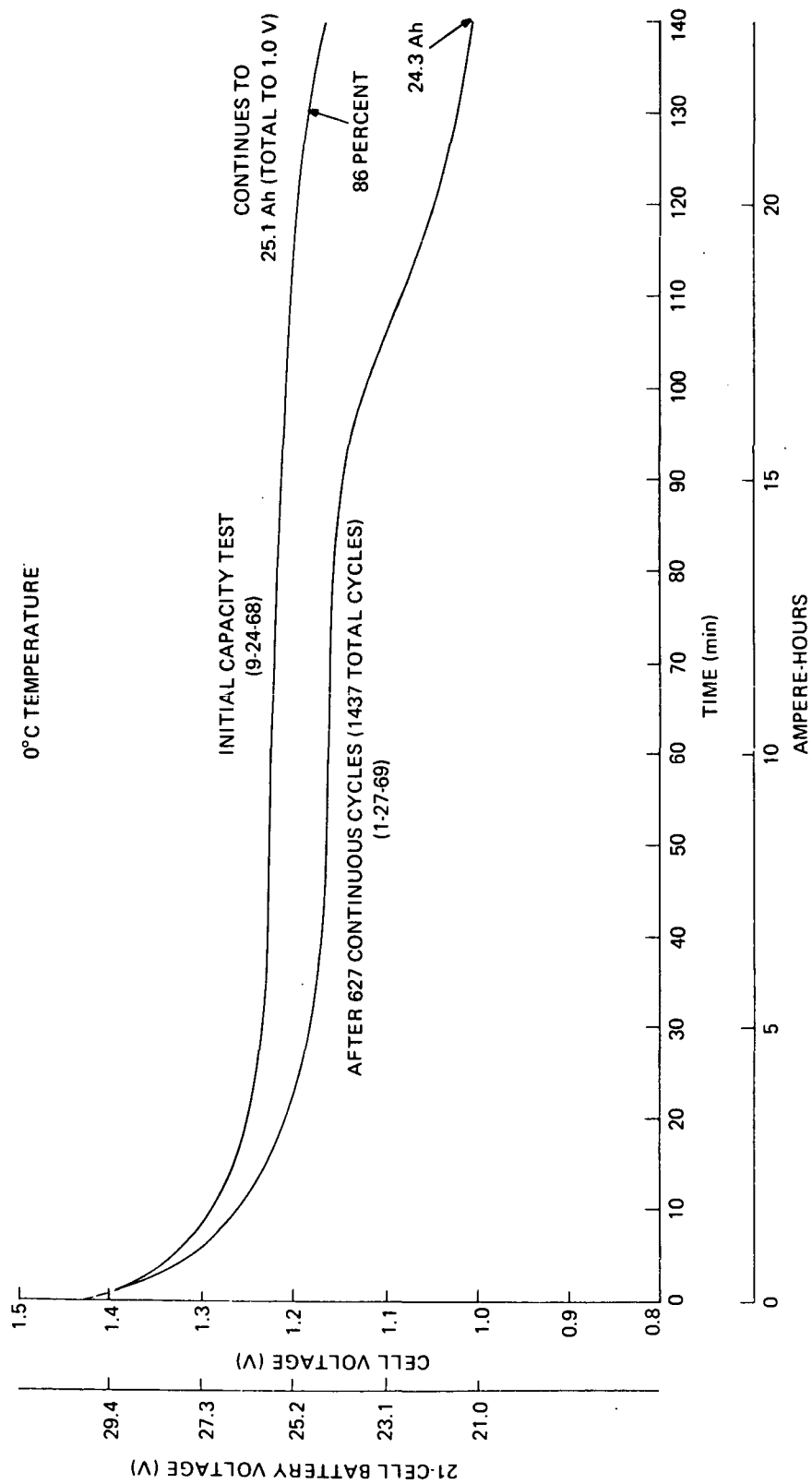


Figure 5. Voltage profile for 10-A discharge for precycling and after 627 cycles (battery assemblies 25A and 26A).

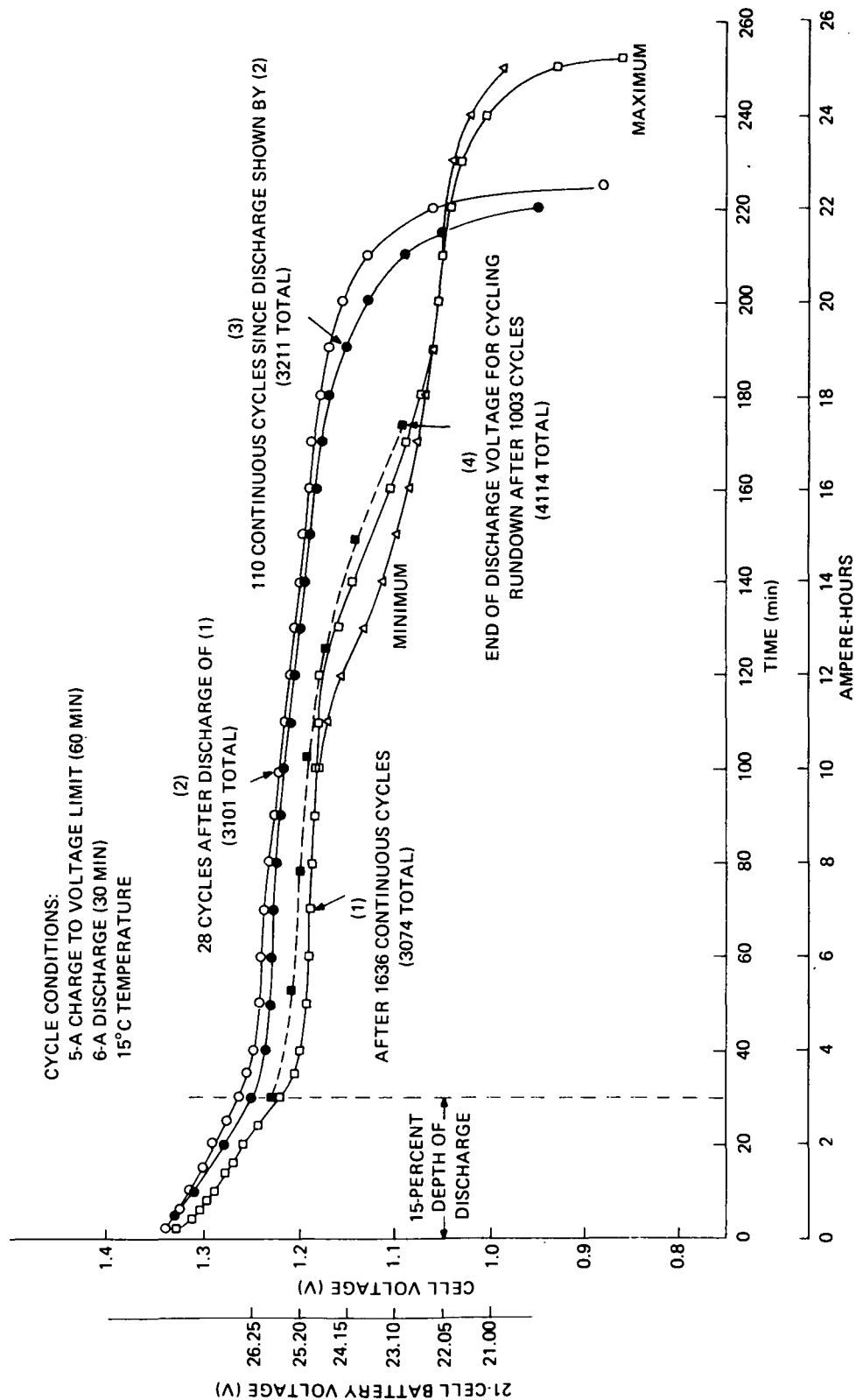


Figure 6. Voltage profile for 6.0-A discharge after various numbers of consecutive cycles (battery assemblies 25A and 26A).



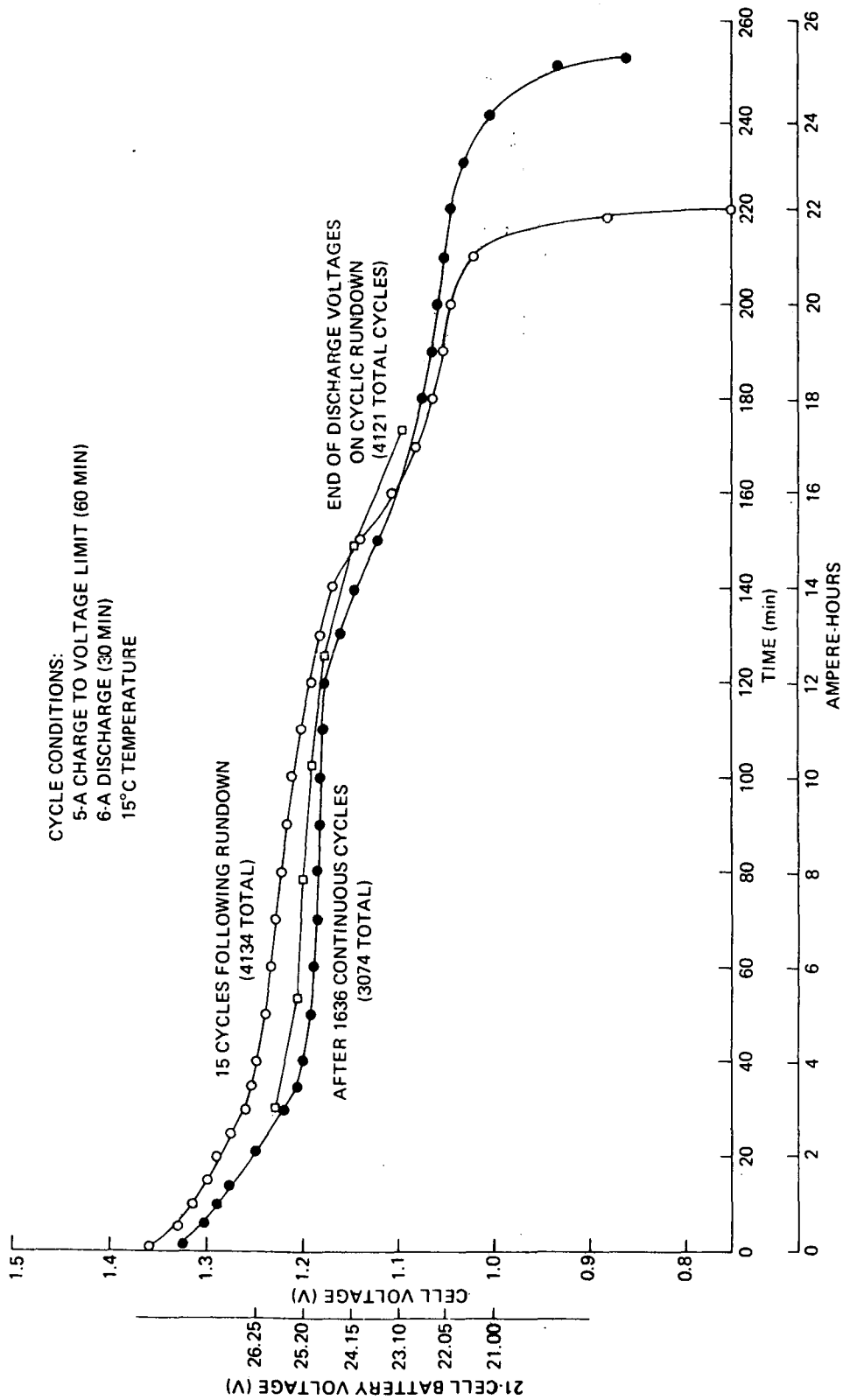


Figure 7. Voltage profile for 6.0-A discharge showing the effects of a partial capacity discharge (battery assemblies 25A and 26A).

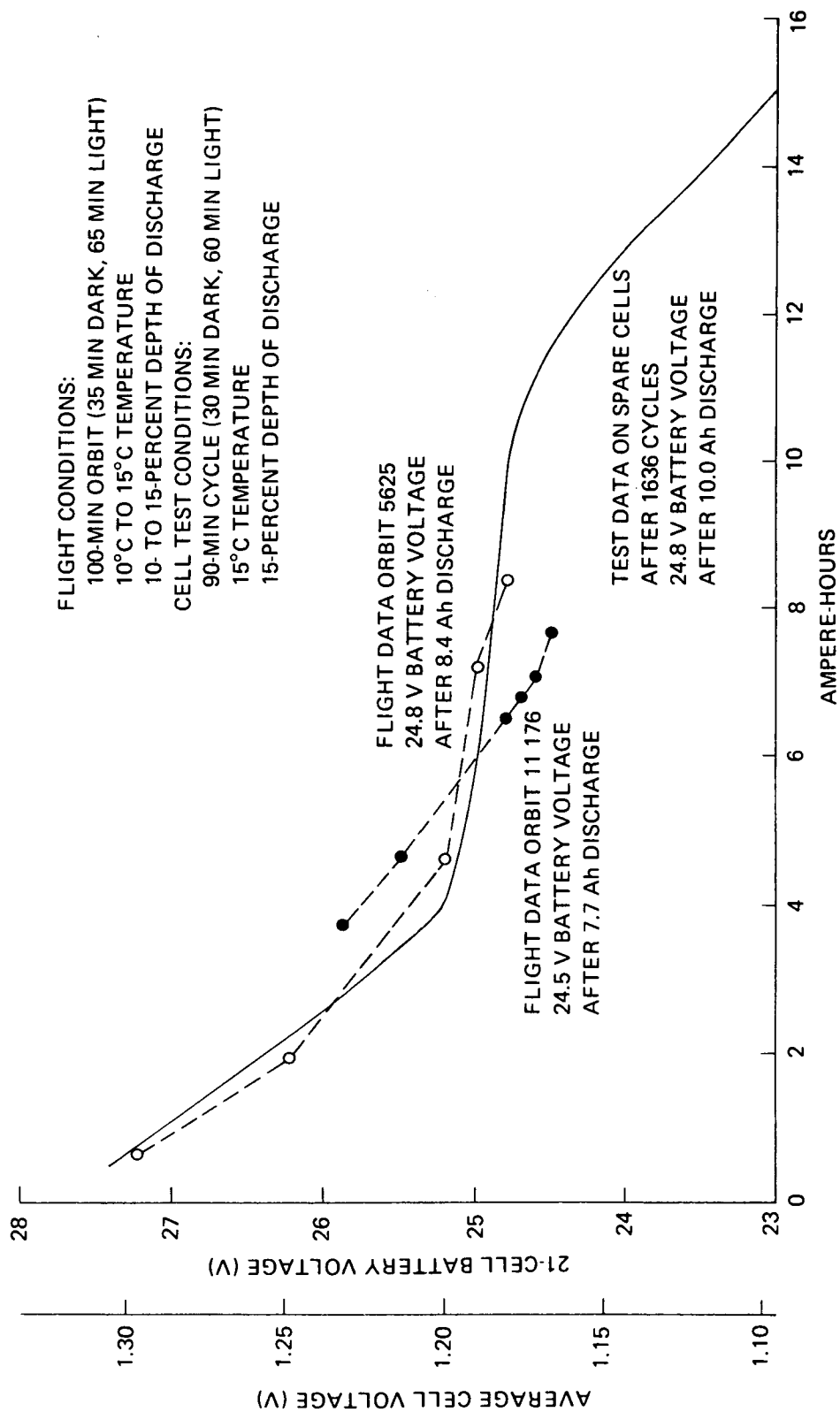


Figure 8. Comparison of discharge voltages from OAO 2 flight-battery data and cell-test data.

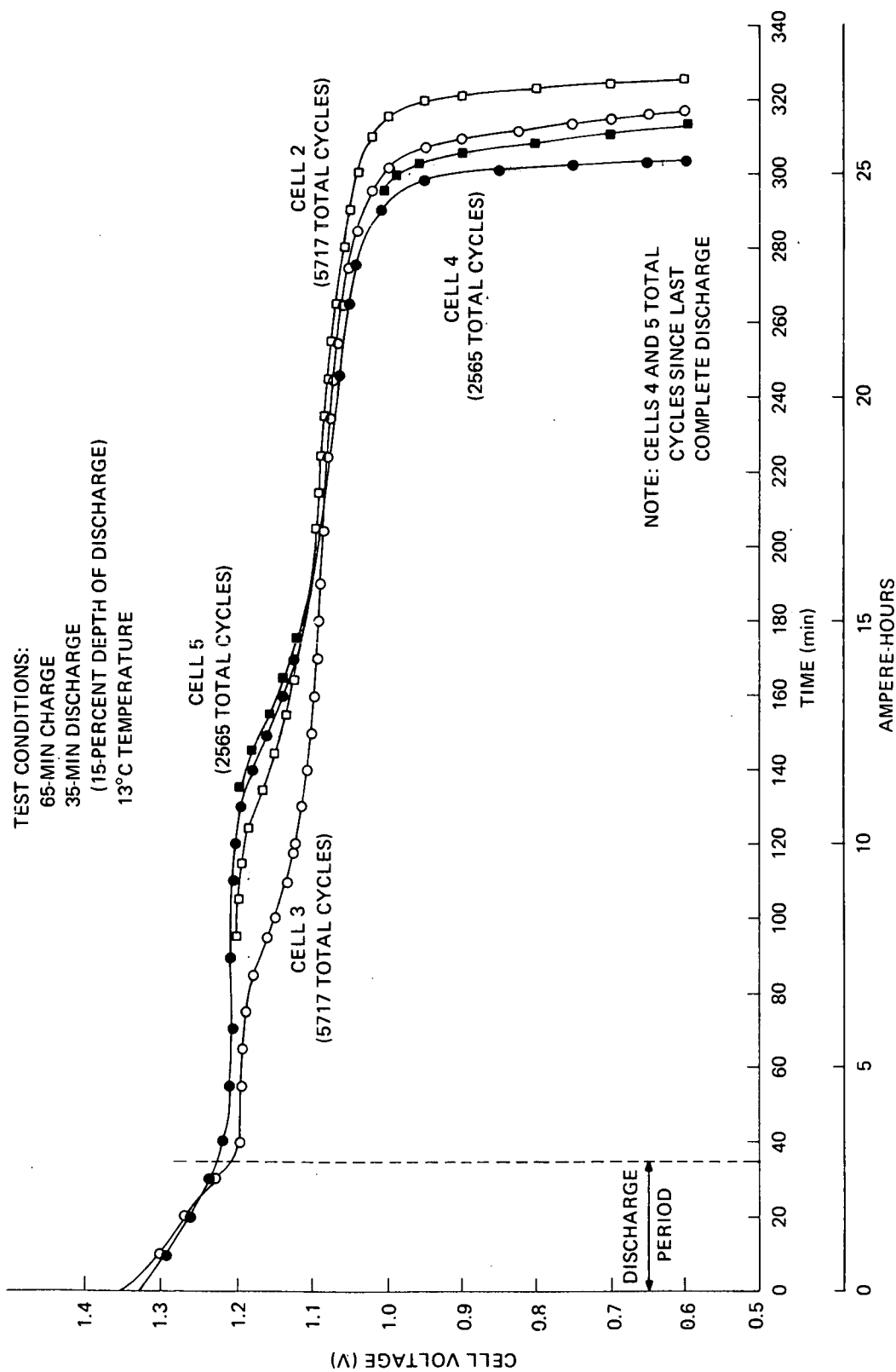


Figure 9. Voltage profile for 5.0-A discharge comparing voltage degradation of cells completing 2565 cycles with those completing 5717 cycles (battery assemblies 32 and 33).

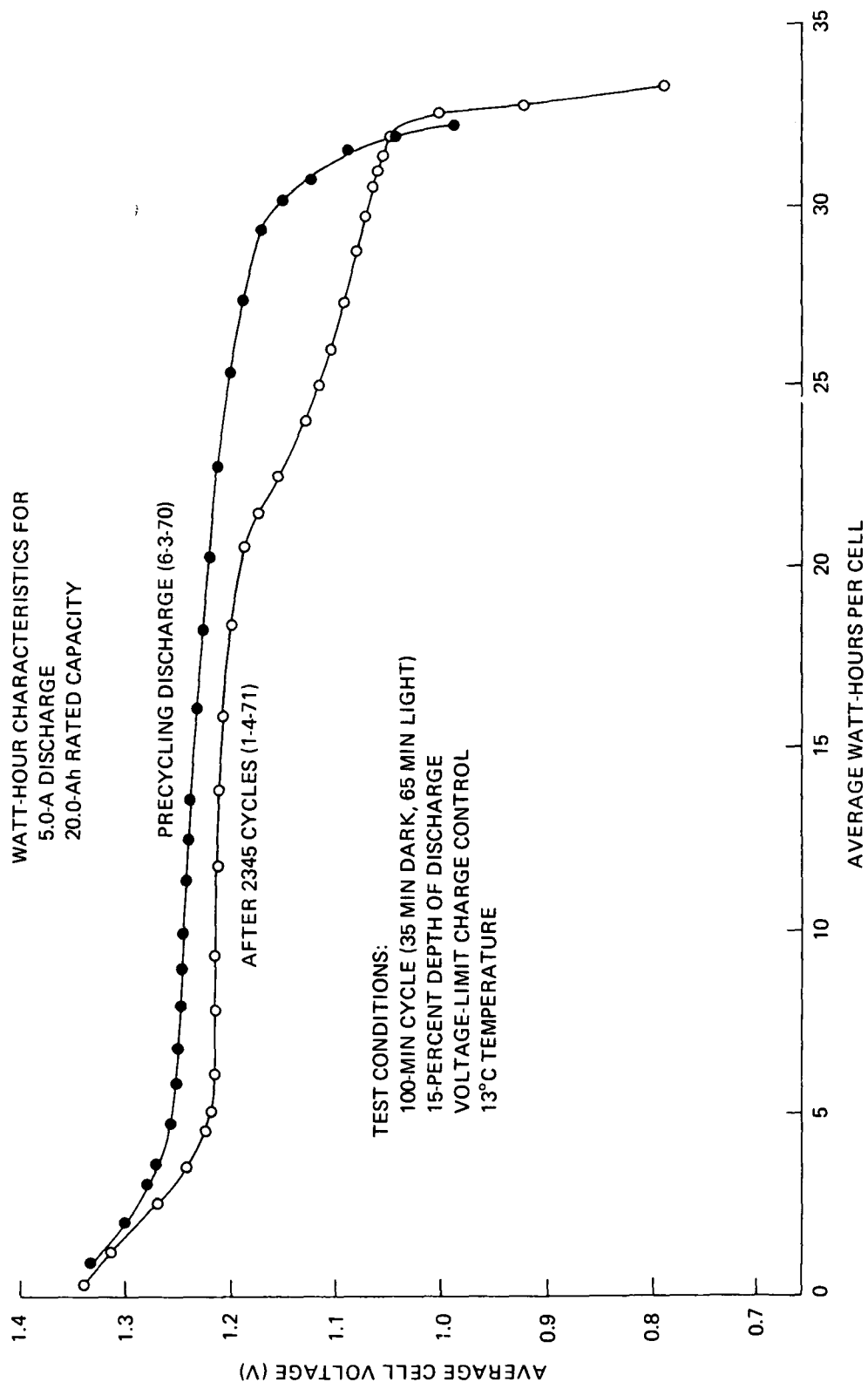


Figure 10. Comparison of precycling watt-hour characteristics with characteristics after 2345 continuous cycles (battery assemblies 32 and 33).

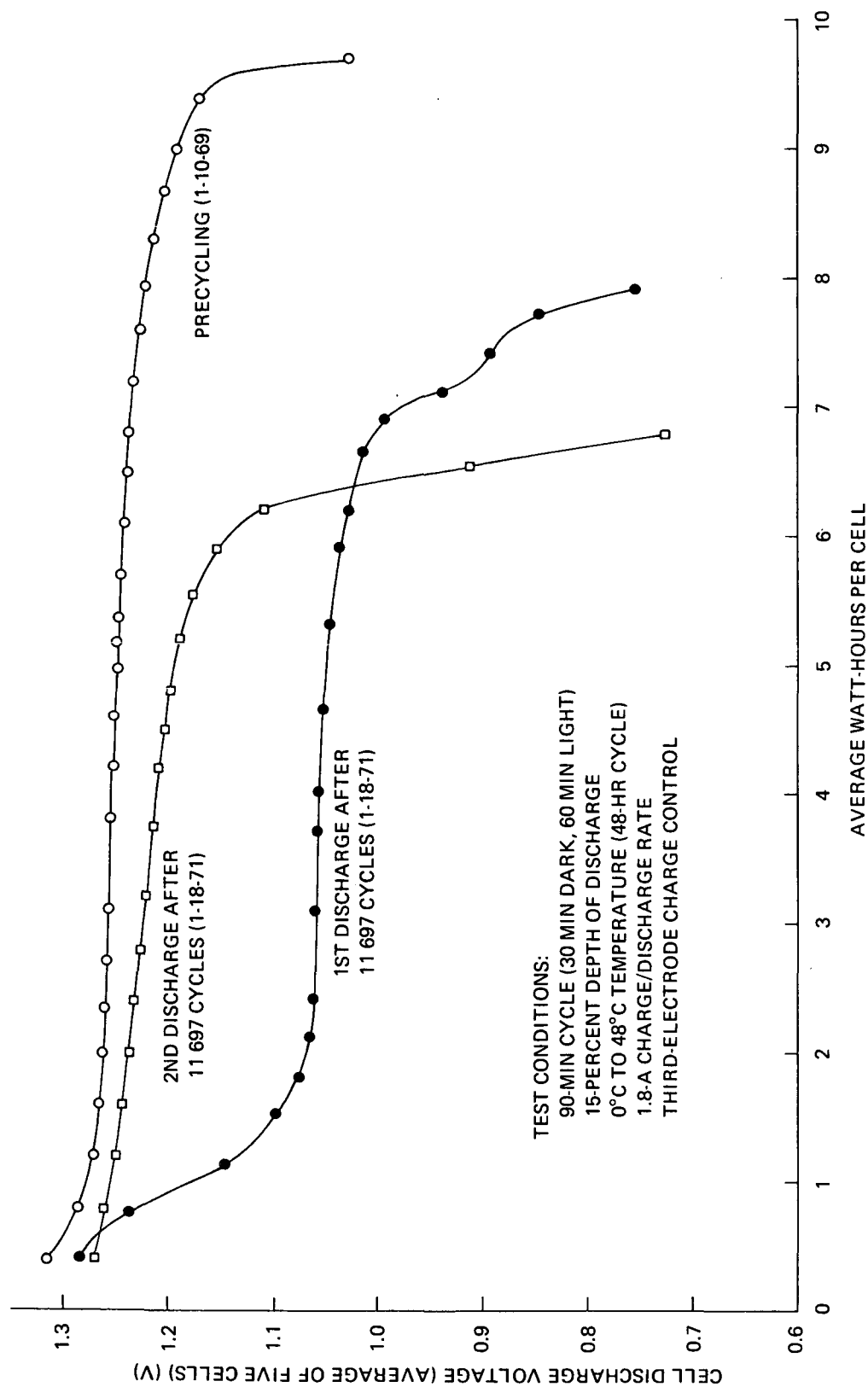


Figure 11. Comparison of watt-hour characteristics after 2 years of cycling (11 697 cycles) with precycling characteristics for a 6.0-Ah nickel-cadmium cell.